Skin Temperature Feedback Increases Thermoregulatory Efficiency and Decreases Required Microclimate Cooling Power

Samuel N. Cheuvront, Ph.D., Scott J. Montain, Ph.D.,
Lou Ann Stephenson, Ph.D., Michael N. Sawka, Ph.D.
U.S. Army Research Institute of Environmental Medicine
Thermal and Mountain Medicine Division
Kansas Street, Building 42
Natick, MA 01760-5007

samuel.n.cheuvront@us.army.mil

ABSTRACT

Personal protective equipment (PPE) markedly increases heat strain, reduces work performance, and increases the incidence of heat casualties. Microclimate cooling (MCC) technologies have been successfully used to alleviate this heat strain in mounted soldiers, but cooling limitations, power and weight restrictions do not currently make this technology applicable to dismounted soldiers. This composite of studies investigated the potential for intermittent-regional cooling and skin temperature feedback approaches to better enable MCC systems for the dismounted soldier. ***PURPOSE:*** *The purposes of this study were to 1) determine, using a variety of intermittent cooling paradigms, the optimal skin temperature for maximizing thermoregulatory efficiency, and 2) examine the potential power savings associated with using biofeedback to maintain optimal skin temperature.* ***METHODS:*** *Two studies were conducted using the same facilities and test equipment. In study one, 5 male soldiers exercised moderately (~500W) in a warm environment (30°C, 30%rh) while wearing PPE (clo: 2.1; i_m/clo: .32) over a water-perfused (21ºC) liquid MCC garment covering the head, chest, back, and legs (72% of body surface area, BSA). All four body regions were independently controlled. A matrix of six randomized trials was conducted in which conventional MCC (constant perfusion, CP), no MCC (NC), or 4 trials of intermittent and regional (IR_{1-4}) MCC was provided. IR_{1-4} was time-activated and on:off cooling ratios and the % BSA cooled were systematically varied. In study two, 8 male soldiers were subjected to the same conditions as study one, but only three trials were performed to include CP, IR_2 (2 min on: 2 min off, 72% BSA), and skin temperature feedback (STF, 72% BSA) using a skin temperature range of 33-35°C. Heart rate (HR), body core (T_c) and skin temperatures (T_{sk}) were measured at regular intervals in both studies.* ***RESULTS:*** *In study one, all IR_{1-4} paradigms significantly reduced physiological strain compared with NC (P<0.05) and were similar to CP (P>0.05). In CP, T_{sk} was lowered to ~32°C and tissue insulation increased. In NC, T_{sk} rose quickly to 36ºC and HR increased exponentially. In IR_{1-4}, T_{sk} fluctuated between 33-35ºC, which improved thermoregulatory efficiency by maintaining heat flux similar to CP over a smaller average BSA (18 or 36%). The variety of time activated on:off ratios made little difference to the results. In study two, IR_2 and STF again reduced physiological strain similar to CP (P>0.05), but the power required for STF was lowest (122±18 W), followed by IR_2 (169±16 W), and CP (224±15 W) (P<0.05, successive).* ***CONCLUSION:*** *The use of STF to maintain T_{sk} between 33-35ºC improves thermoregulatory efficiency and decreases MCC power requirements by 45%. This potential breakthrough has direct application for the dismounted soldier, Objective Force Warrior, and Homeland Defense. Authors' views; not official U.S. Army or DoD policy.*

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14. ABSTRACT

Personal protective equipment (PPE) markedly increases heat strain, reduces work performance, and increases the incidence of heat casualties. Microclimate cooling (MCC) technologies have been successfully used to alleviate this heat strain in mounted soldiers, but cooling limitations, power and weight restrictions do not currently make this technology applicable to dismounted soldiers. This composite of studies investigated the potential for intermittent-regional cooling and skin temperature feedback approaches to better enable MCC systems for the dismounted soldier. PURPOSE: The purposes of this study were to 1) determine, using a variety of intermittent cooling paradigms, the optimal skin temperature for maximizing thermoregulatory efficiency, and 2) examine the potential power savings associated with using biofeedback to maintain optimal skin temperature. METHODS: Two studies were conducted using the same facilities and test equipment. In study one, 5 male soldiers exercised moderately (~500W) in a warm environment (30°C, 30%rh) while wearing PPE (clo: 2.1; im/clo: .32) over a water-perfused (21ºC) liquid MCC garment covering the head, chest, back, and legs (72% of body surface area, BSA). All four body regions were independently controlled. A matrix of six randomized trials was conducted in which conventional MCC (constant perfusion, CP), no MCC (NC), or 4 trials of intermittent and regional (IR1-4) MCC was provided. IR1-4 was time-activated and on:off cooling ratios and the % BSA cooled were systematically varied. In study two, 8 male soldiers were subjected to the same conditions as study one, but only three trials were performed to include CP, IR2 (2 min on: 2 min off, 72% BSA), and skin temperature feedback (STF, 72% BSA) using a skin temperature range of 33-35°C. Heart rate (HR), body core (Tc) and skin temperatures (Tsk) were measured at regular intervals in both studies. RESULTS: In study one, all IR1-4 paradigms significantly reduced physiological strain compared with NC ($P<0.05$) and were similar to CP ($P>0.05$). In CP, Tsk was lowered to ~32°C and tissue insulation increased. In NC, Tsk rose quickly to 36ºC and HR increased exponentially. In IR1-4, Tsk fluctuated between 33-35ºC, which improved thermoregulatory efficiency by maintaining heat flux similar to CP over a smaller average BSA (18 or 36%). The variety of time activated on:off ratios made little difference to the results. In study two, IR2 and STF again reduced physiological strain similar to CP ($P>0.05$), but the power required for STF was lowest (122±18 W), followed by IR2 (169±16 W), and CP (224±15 W) ($P<0.05$, successive). CONCLUSION: The use of STF to maintain Tsk between 33-35ºC improves thermoregulatory efficiency and decreases MCC power requirements by 45%. This potential breakthrough has direct application for the dismounted soldier, Objective Force Warrior, and Homeland Defense. Authors views; not official U.S. Army or DoD policy.

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1.0 INTRODUCTION

Personal protective equipment (PPE) markedly increases heat strain, reduces work performance, and increases the incidence of heat casualties. Microclimate cooling (MCC) technologies have been successfully used to alleviate heat strain and sustain performance [4] (Figure 1) in mounted soldiers, but cooling limitations, power and weight restrictions do not currently make this technology applicable to dismounted soldiers. Not only does the provision of substantial MCC require a large power supply, but conventional (i.e., continuous) MCC approaches can result in constriction of the cutaneous vasculature. Overcooling increases tissue insulation (I_t), decreases convective heat transfer from the body core, and reduces the MCC garment – to – skin (T_{sk}) gradient, thus theoretically reducing MCC operating efficiency [1]. This is particularly true when the thermal demands of the wearer are not constant. Automated control of MCC garments using various biofeedback signals have been investigated [2] [3] for their potential to improve the practicality of MCC relative to changing needs in real-time, but no comparison of an automated approach to simpler and more conventional solutions for reducing heat strain had been attempted.

A series of studies [1] [5] [6] [7] were undertaken to compare the bio-thermal responses to automated and non-automated MCC solutions for reducing heat strain. Particular interest was in understanding the potential for automated MCC to reduce the combined power and size of MCC systems for the dismounted soldier. The purposes of this research were to 1) use a variety of intermittent cooling paradigms in humans combined with modelling simulations to determine the optimal T_{sk} for maximizing thermoregulatory efficiency, and 2) examine the potential power savings associated with using biofeedback to maintain an optimal T_{sk} temperature range.

2.0 METHODS

Two human studies were conducted using the same facilities and test equipment. In study one [1] 5 male soldiers exercised moderately (~500W) in a warm environment (30°C, 30%rh) while wearing PPE (clo: 2.1; i_m/clo: .32) over a water-perfused (21ºC) liquid MCC garment covering the head, chest, back, and legs (72% of body surface area, BSA). All four body regions were independently controlled. A matrix of six randomized trials was conducted in which conventional MCC (continuous perfusion, CP), no MCC (NC), or 4 trials of intermittent and regional (IR_{1-4}) MCC was provided. IR_{1-4} was time-activated and on:off cooling ratios and the % BSA cooled were systematically varied. Additional metabolic rates and inlet water temperatures were later modelled for additional insight [7]. In study two [5] [6] 8 male soldiers were subjected to the same conditions as study one, but only three trials were performed to include CP, IR_2 (2 min on: 2 min off, 72% BSA), and skin temperature feedback (STF, 72% BSA) using a T_{sk} range of 33 – 35°C. Heart rate (HR), body core (T_c), mean T_{sk}, and ratings of thermal comfort (TC) were measured at regular intervals.

3.0 RESULTS

In study one, all IR_{1-4} paradigms significantly reduced physiological strain compared with NC ($P<0.05$) and were similar to CP ($P>0.05$). In CP, T_{sk} was lowered to ~32°C and tissue insulation (I_t) increased (Figure 2A). In NC, T_{sk} rose quickly to 36ºC and HR increased exponentially (Figure 2B). In IR_{1-4}, T_{sk} fluctuated between 33 – 35ºC (Figure 3), which improved theoretical thermoregulatory efficiency (> 100%) by maintaining heat flux similar to CP over a smaller average BSA [1] (Figure 2A). The variety of time activated on:off ratios made little difference to the results and suggested an optimal T_{sk} range of 33 – 35°C (Figure 2A/B). Modelling different options for metabolic rate and coolant inlet temperature [7], it became clear that the

complexity of situational cooling needs would require a bio-engineering feedback approach. In study two, IR_2 and STF again reduced physiological strain [5] and TC [6] similar to CP (P>0.05), but the power required for STF was lowest (122±18 W), followed by IR_2 (169±16 W), and CP (224±15 W) (P<0.05, successive) (Figure 4) [5].

Figure 1: Relationship between MCC and endurance times at selected metabolic rates and wearing NBC protective clothing in a desert environment. From: [4].

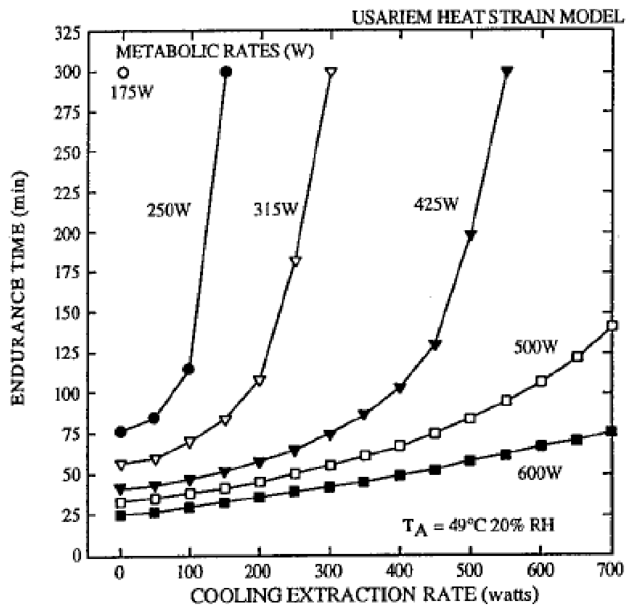


Figure 2: (A) Mean tissue insulation (I_t) and theoretical cooling efficiency shown as a function of mean skin temperature. (B) Curvilinear relationship between ΔHR and T_{sk}. Shaded region represents optimal T_{sk} range for reducing cardiovascular strain while maximizing cooling efficiency. Adapted from [1].

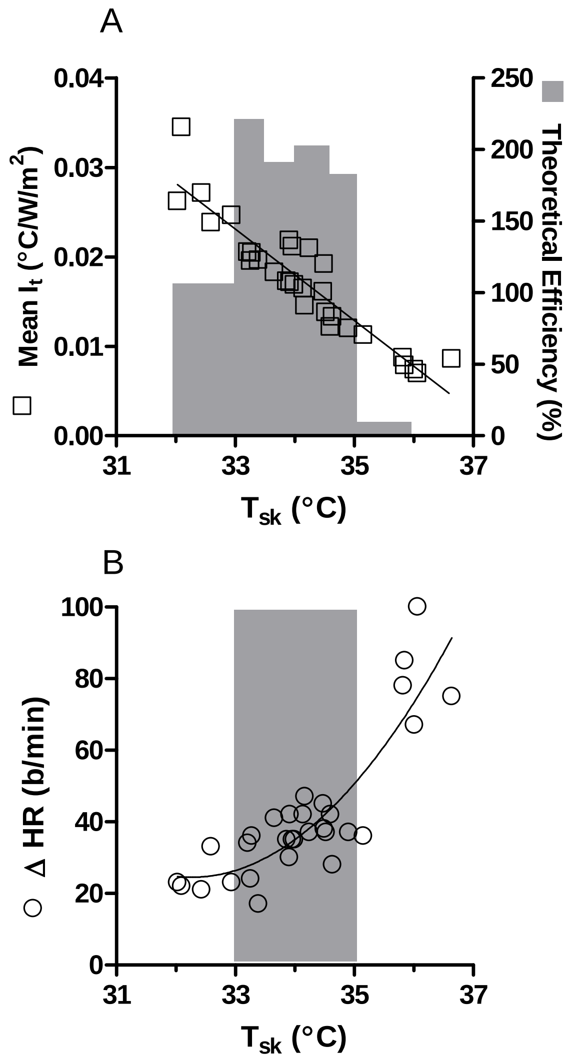


Figure 3: Effect of cooling paradigms on variability of local thigh temperature. Data represent the mean for all subjects measured continuously. Shaded region represents optimal T_{sk} range for reducing cardiovascular strain while maximizing cooling efficiency. From: [1].

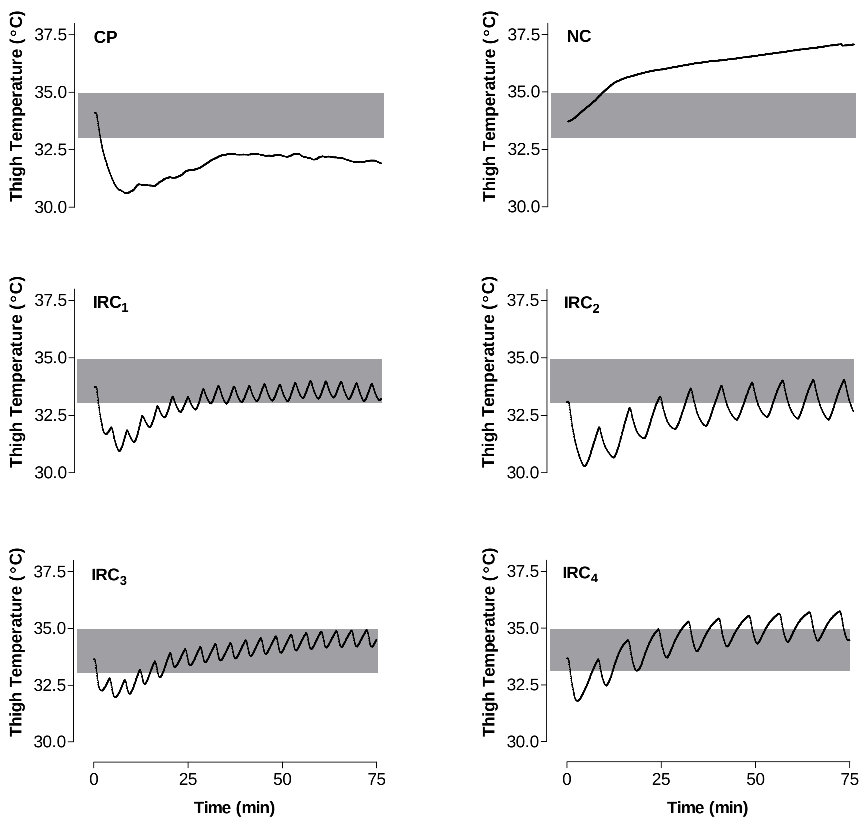
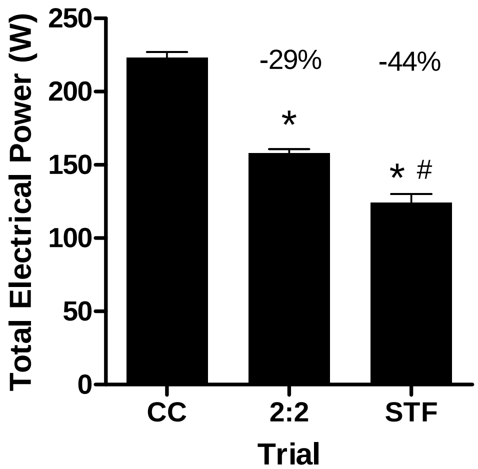


Figure 4: Electrical power consumption using conventional constant cooling (CC), intermittent regional cooling (programmed for 2-min on: 2-min off), and skin temperature feedback (STF) to maintain T_{sk} at 33 –35°C. Adapted from [5].



4.0 CONCLUSIONS

STF as a methodology for maintaining T_{sk} within the narrow range of 33 – 35ºC (European Patent no.: 1708586; U.S. Patent Pending) reduces heat strain similarly to constant cooling paradigms, improves thermoregulatory efficiency, and decreases MCC power requirements. The vasomotor response to a T_{sk} range 33 – 35°C appears optimal for simultaneously minimizing physiological strain while maximizing power efficiency at the MCC – T_{sk} interface. This potential breakthrough has direct application for the dismounted soldier, Objective Force Warrior, and Homeland Defense.

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The opinions or assertions contained herein are the private views of the authors and should not be construed as official or reflecting the views of the Army of the Department of Defense. Approved for public release: distribution unlimited.

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